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Rill density prediction and flow velocity distributions on agricultural areas in the Pacific Northwest

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Abstract

This research focused on rill formation, rill density, and associated flow velocity distribution in rills at the field level and with different tillage treatments in the inland Pacific Northwest. The study was conducted by applying flow at three different rates under winter conditions, which provides the greatest potential for rill formation. The following tillage treatments were tested: chisel plow, moldboard plow, conventional seedbed tillage, and untilled stubble from no-till seeded peas. Twelve plots of 7.3 m^2 were established for each tillage treatment and flow applied on them. The conventional seedbed tillage plots were the most susceptible to rill formation, with one or two resultant rills per meter. On the opposite, the untilled stubble plots did not form rills in most of the cases. Increase in applied flow, soil moisture content, and slope appeared to favor rill formation, while the effect of random roughness and residue was the opposite. By including these variables, an equation for predicting rill density was developed. Rill flow velocity distributions were clearly different for each tillage treatment. Higher flow velocities implied the formation of more rills. At least 0.35 m^2/m^2 of residue cover was necessary to reduce in a half the average flow velocity in the unfilled stubble plots respect to the conventional seedbed plots. Therefore, the use of untilled stubble tillage system is recommended to minimize soil erosion. These results provide information for advancing the understanding of the rill erosion process.

Keywords: Flow velocity; Rill; Rill density; Rill formation; Roughness; Soil erosion; Transport capacity

1. Introduction

Rill formation is the predominant erosion process in the Northwestern Wheat and Range Region (NWRR) of the United States, an area including portions of Idaho, Oregon, and Washington (Austin, 1965). About 90% of soil loss in this region is caused

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Fig. 1. Rill erosion in an agricultural field. State of Washington, U.S. Pacific Northwest.

by rill erosion (Renard et al., 1997). In the NWRR, winter and spring wheat are produced in soils that suffer variable periods of freezing and thawing; conditions that promote soil erosion (Fig. 1). According to Wischmeier and Smith (1978), 90% of the erosion in the Pacific Northwest area (which includes the NWRR), is associated with soil thawing processes and snowmelt. Because soil erosion often causes economic loss, negatively affects soil conditions, and creates environmental problems, it is important to understand the factors that contribute to the erosion process and subsequent formation of rills.

The availability of extensive data and the increased knowledge about the mechanisms and dynamics of soil erosion have allowed researchers to develop empirical and theoretical soil erosion models such as Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997) and Water Erosion Prediction Project (WEPP) (Flanagan and Nearing, 1995). However, considerations of rill development and rill erosion in these models are limited. For the NWRR, RUSLE assigns a rill erosion ratio of 90% to determine the equivalent rainfall-runoff erosivity factor (Renard et al., 1997). In WEPP, a default value of one rill per meter was assumed based on the study by Gilley et al. (1990) conducted on different types of soil in the United States without distinguishing between tillage systems. In addition, as noted by Favis-Mortlock et al. (2000), the hydrological efficiency of each rill was assumed to be similar. Therefore, differences in flow velocities are not recognized. Considering that rill erosion is the principal acknowledged mechanism of soil loss under conventional tillage in the NWRR, there is a need for advancing the understanding of the basic processes and mechanisms of rill formation, such as rill density and distribution, and the magnitude of flow rate and associated transport capacity.

Limited research exists concerning rill formation and rill density. Generally, reported experiments have been conducted under laboratory conditions, often by using re-created soil structures placed in flumes (Foster et al., 1984; Bryan and Poesen, 1989; Slattery and Bryan, 1992). Field experiments, when performed, have often been conducted with pre-formed rills (Van Liew and Saxton, 1983; Elliot et al., 1989). Beyond the weather-related influence, the factors dictating the initiation and development of rills remain unclear. Primarily, this is due to the use of different techniques for experimentation, but also because of the variability in the substrates in which rills develop. From the available studies on this topic, the factors that are related to rill formation and rill density can be classified in (1) spatial factors, and (2) hydraulic factors.

The spatial factors influence the location and density of rills and relate to the variability of the soil properties and the landscape. For example, it has been observed that water flow initially concentrates in areas of depression. At these depression points there is a greater possibility for rill initiation if the flow is sufficiently high. However, if there are no depressions, water will create incisions in areas where the soil does not have enough cohesion or strength to resist the hydraulic stress from the water flow. These observations suggest that some of the main factors governing rill characteristics could be the stress caused by the flow, the roughness of the soil surface, the slope gradient, and the erodibility of the soil (Van Liew and Saxton, 1983; Foster et al., 1984; Bryan and Poesen, 1989; Gilley et al., 1990; Slattery and Bryan, 1992; Obiechefu and Morgan, 1994; Favis-Mortlock et al., 2000).

The hydraulic factors consider flow-related parameters. For example, through flume experiments, both Slattery and Bryan (1992) and Obiechefu and Morgan (1994), agreed that rills were initiated by the development of a knickpoint. Supercritical flow and waves (as opposed to a hydraulic threshold) created the conditions critical for knickpoint formation (Slattery and Bryan, 1992). Obiechefu and Morgan (1994) cited slope and discharge as critical factors for rill initiation, but they also pointed to hydraulic conditions from laminar to turbulent regimes, and from subcritical to supercritical, as important factors to be considered. In another study, Bryan and Rockwell (1998) stated that, in areas where spring snowmelt and rainfall caused runoff, soil moisture content was the primary factor for the development of rills. Based on the idea of 'competition for runoff between rills, Favis-Mortlock et al. (2000) created a simulation model (RillGrowl) for rill initiation and development. According to the developers, RillGrowl has some limitations that needed to be addressed through the development of a new version of the model. Specifically, three limitations were identified: (1) lack of consideration for deposition; (2) operation in an unreal time domain ('packets' of runoff moving individually and not concurrently in a grid); and (3) oversimplification of the hydraulics.

The hydraulic considerations must involve flow velocity, which is a key factor in the energy needed for rill development and soil erosion. Flow velocity has been directly related to rates of soil loss (Nearing et al., 1999; Mancilla, 2001), and then to rill formation and development (Lei et al., 1998). Rill flow velocity has also been related to the transport capacity of the flow and thus to sediment delivery (Lei et al., 1998; Mancilla, 2001). Therefore, the frequency and erosion intensity of rills is determined by the flow velocity distribution in the field.

This research effort focused on rill formation, rill density, and flow velocity distributions. Specific objectives of this paper were to: (1) present a relationship for predicting the number of rills generated from different tillage treatments based on variables that can be determined under field conditions, and (2) determine the density distribution of velocities reached by the flow along the rills.

The distribution of flow velocities was required to establish sediment transport relationships in rills, that will be addressed in future studies.

2. Material and methods

2.1. Experimental design

Fieldwork was performed on the Palouse Conservation Field Station (PCFS) of the USDA Agricultural Research Service, located 3 km northwest of Pullman, WA, USA. This area is part of the NWRR. Palouse silt-loam soil is predominant in this area. This soil has 20.1% clay, 70.1% silt, and 9.8% sand, with organic matter estimated at 2.6% (Nicks et al., 1995). Rill generation experiments were conducted with varying flow applications on runoff plots with different tillage treatments. In the season prior to this research, the field had been cropped with no-till seeded peas.

At the PCFS, an approximate area of 0.4 ha with average longitudinal slope of 23% was divided into four different tillage treatments areas: untilled stubble from no-till seeded peas (referred to as untilled stubble henceforth), conventional seedbed tillage (chisel plow, disk, and harrow), moldboard plow primary tillage only, and chisel plow primary tillage only. The areas were tilled on the contour in November 2000. Afterwards, 12 plots of 7.3 m^2 (1.83 m wide and 4 m long) were established in each treatment (48 plots in total) in the direction of the main slope (Fig. 2). In the interest of accurately reproducing existing field conditions, the plots were not protected from rain or snow. The experiments were conducted between December 2000 and April 2001. During the experiments, water was applied at three selected rates per

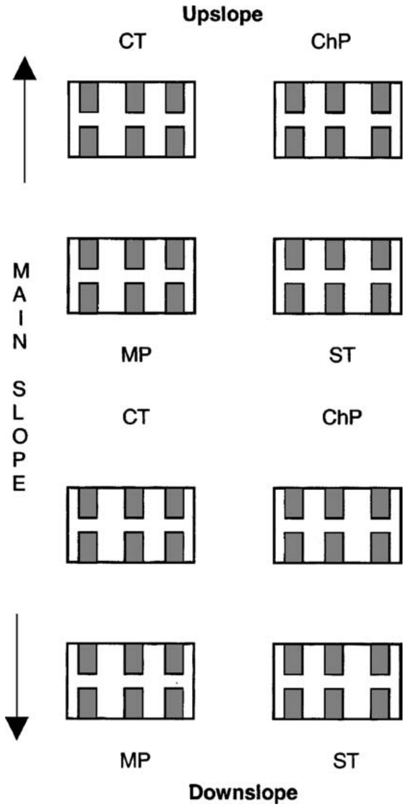

Fig. 2. Experimental design. Schematic representation of the different tillage practices tested in this research. The correspondent plots are in grey color. In the figure, CT: conventional seedbed tillage; ChP: chisel plow primary tillage; MP: moldboard plow primary tillage; ST: untilled stubble.

meter width of plot over the four tillage treatments: 8.3 L/min/m (2.2 US gal/min/m), 12.4 L/min/m (3.3 US gal/min/m), and 16.6 L/min/m (4.4 US gal/min/m), for a period of 85, 56, and 42 min, respectively. Under natural conditions, runoff rates are tillage-dependent. However, the same water runoff rates were applied in this research to make comparison between treatments. Each water application rate was replicated on four plots of the same tillage treatment, with one application per plot. The applied water volumes matched estimates of the Cligen simulator (Nicks et al., 1995) for a typical Palouse hillslope winter situation (76.2 m long, and soils having an antecedent moisture condition so high that infiltration was negligible). Under this assumption, Cligen indicated that the applied water rates would correspond to the runoff yielded by rainfall intensities from 11.9 mm/h to 23.8 mm/h. For these calculations, Cligen used an observed time record length of 44 years.

2.2. Water application system

A water application unit was specially constructed for this study. This system applied uniform amounts of water to the upslope end of the plots. The system was composed of two water tanks, a pump, 5 cm diameter hoses, adapters, a valve, a flow meter, a manifold, and a box for dissipating the kinetic energy of the water exiting the manifold. The 1000 L capacity water tank was the main source of water. The tank was refilled during the experiment from another tank of 700 L capacity. The 1000 L tank was connected to a pump with a four-cycle gasoline engine that produced the pressure needed to generate the required water application rate. From the pump, 5 cm diameter hoses conveyed the water to a maximum distance of 100 m. The end of the hose was connected to a water valve, which allowed regulation of the flow rate. The water valve was linked to a flow meter, which in turn was connected to a manifold built from a 5 cm PVC pipe with eight equally-separated 4 mm diameter holes for emitting water. The manifold was placed horizontally into a metal box so that the water spray energy was mostly dissipated by the impact against the sides and front of the metal box. The bottom of the metal box was a 1.83 m wide apron, flat and horizontally leveled, so the water ran from this surface to the ground equally distributed. Knit cloth was placed at the end of the apron to ensure that excessive water energy could be reduced before reaching the soil surface.

2.3. Soil surface roughness determinations

As described above, soil roughness is a factor related to the formation of rills. Therefore, prior to the experiments, random roughness was measured on each plot using a rill-meter (McCool et al., 1981). The rill-meter determined elevation differences every 1.27 cm using 145 pins positioned along the contour lines. Seventeen rill-meter sections were established from the bottom to the top of each plot, with a 25 cm space between each section. In each section, the rill-meter was leveled horizontally, the pins were released, and a picture of the pin heights was taken with a digital camera. From the picture and the previous scanning, a baseline was determined by regression analysis from the pin heights. Therefore, there were 17 regression baselines calculated for each plot.

The use of a digital camera allowed for a direct interface with SigmaScan Pro 5.0, the software chosen for scanning and determining the height differences of the pins. The height difference was then converted to real scale through calibration.

From the difference in pin heights relative to the respective baseline, the random roughness of each section was calculated using the formula proposed by Currence and Lovely (1970):

$$\mathrm{rr}_i = \sqrt{\frac{\sum_i (h - \bar{h})^2}{n - 1}} \quad (1)$$

where rr_i corresponds to the standard deviation of the differences with respect to the mean height (or baseline, in this case), $i = 1, 2, 3, \ldots, 17$ is the order of the section number of the plot, h is the difference with respect to the mean height of each pin, $\bar{h}$ is the mean of all those differences in the respective i section, and n is the number of pin heights (or 145 pins in this case). The random roughness (RR) for the whole plot was estimated by using the average of the calculated standard deviations, or:

$$\mathrm{RR} = \frac{\sum_{i=1}^{17} \mathrm{rr}_i}{17} \quad (2)$$

Additional indicators, such as points of minimum height were also determined from the rill-meter technique. However, these indicators were not useful when comparing based on different tillage systems.

2.4. Measurements

2.4.1. Flow velocity

During water application, flow velocities in the plots were determined using fluorescent dye both before and after rills were formed. This methodology has been broadly employed in soil erosion research (Roels, 1984; Line and Meyer, 1988; McIsaac et al., 1996, between others). As recommended by Abrahams et al. (1986), visual observations of flow velocity were made by recording the time in which 50% of the applied dye passed a certain point. Usually this coincides with 80–90% of the maximum width that the dye could reach in the flow (Govers, 1992). The values were then adjusted by flume experiments in order to correct possible eye-sight error. In this case, known flow rates and cross sectional areas allowed the use of Manning's equation to determine real flow velocities, which were compared with dye-estimated values. A linear regression between observed and determined values of flow velocity was then determined, and the field observations of flow velocity were then corrected.

The distance over which velocity was measured in the field was usually 2 m along a straight line. Measurements were taken twice at the same point and as uniformly distributed in time as reasonable.

2.4.2. Rill development and area of cross sections

Rill development was characterized at different cross sections. In each rill cross section the width of the upper part of the rill and the depth of the water flow were measured at three points. At the end of the experiments (and during the experiments for some of the plots), measurements were taken at the rill cross sections located at the first, second, third, and fourth meters of the plots. Both hydraulic radius and wetted perimeter were determined from these measurements. The length of the rill up to the position of each cross section was also measured. Thus, the flow velocity determinations could be corrected for actual distances. Based on the measurements and observations it was determined that a mixture between a rectangular and parabolic shape could characterize the cross sections of the rill. This conclusion coincided with an observation made by Govers (1992). Consequently, the area of a rill cross section was calculated as:

$$A = \frac{5}{6} \mathrm{d}T \quad (3)$$

where A is the area of the cross section, d represents the depth of the water (average of three measurements), and T is the width of the upper part of the respective rill cross section (original rectangular and parabolic shape formulas from USDA-SCS, 1985).

2.4.3. Number and category of rills

The number of rills was determined for the entire plot. The rills were classified as two different types:

- Main rills: rills that transported most of the water and sediment out of the plot, usually larger than the rest of the finer channels in the plot.
- Secondary rills: small channels that usually transported less water than the main rill without removing water from the plot. Normally, these rills were tributaries of the main rills or dissipated before reaching the end of the plot.

This research focused only on main rills. Therefore, in this research the terms ''rills'' and ''main rills'' have the same meaning. The rill number is then defined as the number of main rills reaching the end of the plot. This does not avoid that in real conditions the rills could further combine or diverge.

2.5. Additional determinations

Pertinent parameters of the plots were determined just before the experiments, including the soil moisture content of the first 15 cm of depth (by gravimetric method), soil bulk density, the porosity (as 1−{soil bulk density/soil particle density}), the ridge height, the furrow depth (by graduated ruler), and the proportion of the soil surface covered by residue (by visual observation). In addition, the strength of the soil was measured with a shear vane and longitudinal slope was determined for each plot with a clinometer.

2.6. Analysis of the data

2.6.1. Rill density model

A rill density predictive model was developed for all four tillage treatments and the three applied flow rates. Applied flow, proportion of residue cover, random roughness, antecedent soil moisture content, bulk density, and slope were the predictive variables employed. Additionally, maximum and minimum ridge height, porosity, and degree of saturation were also tested as predictive parameters for the number of rills. The predictive model was determined by the forward selection stepwise regression procedure, which considers the introduction in the model of one variable at the time. Variables with significance levels (p-values) for over 0.05 were discarded. The rill density predictive model was developed by using the number of rills in each plot alone.

To test the performance of the new rill density model, photographic data and records were analyzed from studies conducted in continuous fallow plots at the USDA-ARS Palouse Conservation Field Station between winter seasons 1984–1985 and 1985–1986. For the test, no infiltration was assumed from the precipitation events related to the USDA-ARS data. Only the events that occurred after the first effective runoff were considered for the total precipitation amount in the USDA-ARS plots data. The original values from the USDA-ARS plots were used to apply the respective equation. Then, the result was multiplied by a correction factor and the width of the USDA-ARS plots. The correction factor was assumed as the ratio between the precipitation in the real events and the 1287 L of water applied to each plot in the current study. Only the rills reaching the bottom of the USDA-ARS plots were considered in the total rill count.

2.6.2. Flow velocity distributions

Kernel density estimations for rill flow velocity were developed for each tillage treatment and flow application; thus allowing for effective comparisons between treatments. The variability in flow velocity was related to the hydraulic characteristics of the rills in the different treatments.

3. Results and discussion

3.1. Number of rills

The highest average number of rills was generated in plots subjected to conventional seedbed tillage, followed by moldboard plowed, and then chisel plowed (Table 1). The smallest number of rills was observed in the untilled stubble plots. However, the statistics reflected untilled stubble plots as having significantly fewer rills for the 12.4 L/min/m of applied flow only (Table 1). On the other hand, the resultant number of rills in conventional seedbed tillage plots was significantly higher for all three amounts of applied flow. The average number of rills did not change between 12.4 and 16.6 L/min/m of

Table 1
Resultant average number of rills per meter

Treatment	Flow applied (L/min/m)	Average number of rills (Rills/m)	Tukey's test[a] categories ($\alpha = 0.05$)
MP	8.3	0.55	a
ChP	8.3	0.41	a
ST	8.3	0	a
CT	8.3	1.37	b
MP	12.4	0.96	a
ChP	12.4	0.68	a
ST	12.4	0	b
CT	12.4	1.64	c
MP	16.6	0.96	a
ChP	16.6	0.68	a
ST	16.6	0.41	a
CT	16.6	1.64	b

MP: moldboard plow primary tillage; ChP: chisel plow primary tillage; ST: untilled stubble; CT: conventional seedbed tillage.
[a] Tukey's test performed separately according to flow applied.

applied flow for the three tilled treatments. This suggests that the maximum rill generation would still occur below these flow rates. Competition for water may have prevented the formation of additional rills, as reported by Favis-Mortlock et al. (2000). The water application rate of 8.3 L/min/m was close to the critical value for rill formation in moldboard and chisel plow plots, but fairly excessive for the conventional seedbed tillage plots. Clearly, it was easier for rills to form in the conventional seedbed tillage treatment. These results strongly suggest the need to test flow rates lower than 8.3 L/min/m in future experiments.

On the untilled stubble plots, rills were generated only when 16.6 L/min/m of water was applied, and these rills had the smallest dimensions. Since the 16.6 L/min/m flow rate is unusual in the test region, the formation of rills on untilled stubble treatment is unlikely.

The resultant rill per meter values demonstrates that the WEPP assumption of one rill every meter was consistent with most of the results. This assumption is based on the study by Gilley et al. (1990). However, it is important to consider the case of the conventional seedbed tillage area when 12.4 and 16.6 L/min/m of water was applied. Under such conditions the average was closer to two rills per meter. Therefore, by using clean water as the main source of flow (that certainly included some distortion regarding the reduced length of the plots), a rill spacing of two instead of one rill every meter was more suitable for the conventional seedbed tillage area used in this study.

It is necessary to point out the variability in the resultant number of rills of plots under similar conditions of tillage and flow applied. In the field conditions where this study was conducted, just the flow applied was a totally controlled parameter. Other environmental factors were not constant throughout the experiments, so the resultant inconsistence in rill number was feasible. For more clarity on this respect, a summary of the results for each plot is given in Table 2.

3.2. Model to predict number of rills

Stepwise linear regression analysis of the experimental data resulted in an equation for predicting the number of rills per meter. In the modeling process, taking the respective natural logarithm of the explanatory variables minimized the residual sum of squares. The equation, considering all of the treatment plots is:

$$N = 0.66 + 0.69 \times \ln(\mathrm{Flow}) + 0.91 \times \ln(\mathrm{MC}) + 2.04 \times \ln(\mathrm{S}) - 0.37 \times \ln(\mathrm{RR}) - 0.37 \times \ln(\mathrm{Re}) \quad (4)$$

where N corresponds to the number of rills per meter; Flow, the flow applied in the field (L/min/m); MC, the antecedent volumetric moisture content of the first 15 cm of the soil profile (m^3/m^3); S, the fraction of longitudinal slope (m/m); Re, the fraction of the ground covered by residue (m^2/m^2), and RR corresponds to the random roughness of the field under the determined tillage treatment (m). For each variable, the units are corrected by the respective fitted coefficient. This equation is valid for all the tillage treatments for the flow range applied, and for a volumetric moisture content ranging between 0.21 and 0.55 m^3/m^3, slope between 0.19 and 0.27 (m/m), residue cover between 0.03 and 0.93 (m^2/m^2), and a random roughness between 8.0 and 23 mm (model use value in meters). Statistical details about this equation are in Table 3.

The above equation represents the effect of the major factors affecting rill formation. In this case, both

Table 2
Resultant number of rills for each plot

Plot	Rills/plot	Rills/m	Flow (L/min/m)	Plot (*)	Rills/plot	Rills/m	Flow (L/min/m)
ChP1	1	0.55	8.3	MP1	2	1.09	8.3
ChP2	1	0.55	8.3	MP2	0	0.00	8.3
ChP3	1	0.55	8.3	MP3	1	0.55	8.3
ChP4	0	0.00	8.3	MP4	1	0.55	12.4
ChP5	1	0.55	12.4	MP5	2	1.09	12.4
ChP6	1	0.55	12.4	MP6	2	1.09	12.4
ChP7	2	1.09	12.4	MP7	2	1.09	12.4
ChP8	1	0.55	12.4	MP8	2	1.09	16.6
ChP9	1	0.55	16.6	MP9	2	1.09	16.6
ChP10	1	0.55	16.6	MP10	2	1.09	16.6
ChP11	2	1.09	16.6	MP11	1	0.55	16.6
ChP12	1	0.55	16.6	(*) Due to irregularities in the applied flow, only eleven plots were considered in the analysis			
CT1	3	1.64	8.3	ST1	0	0.00	8.3
CT2	2	1.09	8.3	ST2	0	0.00	8.3
CT3	3	1.64	8.3	ST3	0	0.00	8.3
CT4	2	1.09	8.3	ST4	0	0.00	8.3
CT5	3	1.64	12.4	ST5	0	0.00	12.4
CT6	4	2.19	12.4	ST6	0	0.00	12.4
CT7	2	1.09	12.4	ST7	0	0.00	12.4
CT8	3	1.64	12.4	ST8	0	0.00	12.4
CT9	3	1.64	16.6	ST9	1	0.55	16.6
CT10	4	2.19	16.6	ST10	1	0.55	16.6
CT11	3	1.64	16.6	ST11	1	0.55	16.6
CT12	2	1.09	16.6	ST12	0	0.00	16.6

MP: moldboard plow primary tillage; ChP: chisel plow primary tillage; ST: untilled stubble; CT: conventional seedbed tillage.

flow applied and slope favored higher number of rills. Antecedent soil moisture content also had an effect on the formation of rills. Rills were generated primarily under soil saturation or conditions close to saturation, such as in the study of Bryan and Rockwell (1998), which demonstrated that rill initiation was controlled by saturation conditions more than by hydraulic thresholds. Residue cover and random roughness factors showed an inverse relation with the formation of rills.

The generation of rills in conventional seedbed tillage plots was quick and dynamic, implying a high susceptibility of this tillage treatment to rill formation and soil erosion. In this treatment, the effect of random roughness in reducing both the flow velocity and concentration did not last very long and was easily overcome. Certainly, not much water would be necessary for generating a rill in the conditions of low roughness, low residue, and high moisture content in the plots subjected to the conventional seedbed tillage treatment. On the other hand, due to the high fraction of ground covered by residue, the formation of rills in the plots subjected to untilled stubble and chisel plow tillage was very difficult. The residue tended to obstruct the water passages. In consequence, both the flow velocity and flow concentration were reduced, so the formation of rills was unlikely.

Eq. (4) was tested with data from continuous fallow plots in the winter seasons 1984–1985 and 1985–1986, collected from the USDA-ARS at the Palouse Conservation Field Station. Table 4 indicates the estimated number of rills for the USDA-ARS plots data. The estimates with 8.3 L/min/m of flow rate were closer to the observed values. It was expected that the best approach would be to consider the experimental 8.3 L/min/m as flow applied, because runoff events in this region are unlikely to be more intense. The results indicate that the parameters and assumptions employed in determining the generation of rills are adequate. Certainly, the predictive rill density model has sources for uncertainty. To overcome some of these uncertainties, future studies should consider:

Table 3
Statistical summary for the rill density model

Predictor	Coefficient	S.D. coefficent	T	p	
Regression analysis[a]					
Constant	0.66	1.47	0.45	0.657	
ln(Flow)	0.69	0.17	4.05	0.000	
ln(RR)	−0.37	0.17	−2.12	0.041	
ln(MC)	0.91	0.34	2.64	0.012	
ln(S)	2.04	0.70	2.92	0.006	
ln(Re)	−0.37	0.06	−6.29	0.000	
Analysis of variance					
Source	DF	SS	MS	F	p
Regression	5	13.57	2.71	30.97	0.000
Residual error	41	3.59	0.09		
Total	46	17.16			
Detailed sum of squares					
Source	DF	SS			
ln(Flow)	1	0.92			
ln(RR)	1	0.06			
ln(MC)	1	0.99			
ln(S)	1	8.13			
ln(Re)	1	3.47			

Rills/m = 0.66 + 0.69 ln(Flow) − 0.37 ln(RR) + 0.91 ln(MC) + 2.04 ln(S) − 0.37 ln(Re).

[a] Standard error of estimation = 0.296, R^2 = 79.1%, adjusted R^2 = 76.5%.

(1) The use of lower flow rates. It was clear from the resultant number of rills of the conventional tillage plots that the flow applied was excessive. Smaller amounts of flow should then be tested in this type of tillage treatment.
(2) The increase of the experimental plots width. The 1.83 m width in the plots of the current study induced larger variations in the number of rills under the same tillage system and flow applied. This could certainly affect the quality of the rill predictive model.
(3) The increase in the number of experimental plots. A better definition of the trends in number of rills, so as a larger scope of values in the predictive variables would be obtained if more experimental plots are set.

The development of the rill model is beneficial towards: (1) estimating the number of rills using variables that are relatively easy to measure, so the equation can be incorporated into existing models to more accurately predict soil erosion; and (2) providing information on the importance of each field factor on rill generation. In winter conditions especially, it is clear that soil behavior in the erosion process must certainly relate to multiple variables of difficult or unknown determination. This approach, then, represents a first attempt to relate the rill density to certain variables, but with the understanding that the real scenario involves larger complexity.

3.3. Rill flow velocity distributions

Kernel density estimation of rill flow velocities in the experimental treatments are represented in Fig. 3(a)–(d), for the flow application of 8.3 L/min/m. More detail can be found in Mancilla (2001) or upon request to the authors. In the case of untilled stubble, the flow velocities of plots that did not develop any rills are also included for the purpose of comparison.

In general, the flow velocities increased as the applied flow rate increased, but at a lesser rate. As expected, velocities in untilled stubble plots were the lowest because of the large distribution of residue and the absence of rills. Chisel plow plots (with the second highest level of residue) showed the second slowest flow velocities. Because of the oriented roughness effect in reducing the flow velocity, the moldboard plow plots did not reach flow velocities as much as those measured on the conventional seedbed tillage plots. The highest flow velocities were measured in the conventional seedbed tillage treatment. This coincides

Table 4
Estimated number of rills for the observed Palouse Conservation Field Station plots data from 1984 to 1986, by using predictive Eq. (4)

Situation	Plot 13, 1984–1985	Plot 13, 1985–1986	Plot 36, 1984–1985	Plot 36, 1985–1986
Observed number of rills in plots of dimensions 3.7 m width, 22.3 m long	2–3	5–6	2	3–4
Estimation with Eq. (4), 8.3 L/min/m of flow applied	4	4–5	3	3–4
Estimation with Eq. (4), 12.4 L/min/m of flow applied	5	5–6	4–5	5
Estimation with Eq. (4), 16.6 L/min/m of flow applied	5–6	6–7	5–6	6–7

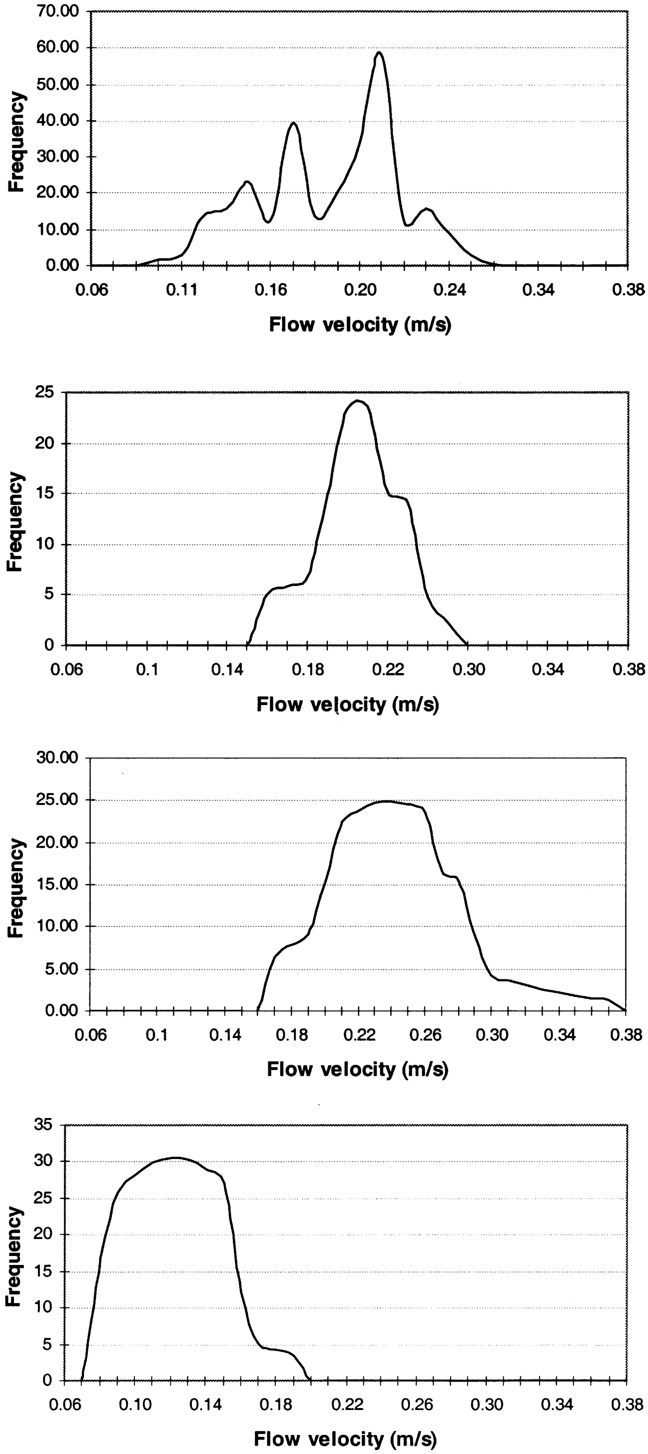

Fig. 3. Rill flow velocity density distributions with 8.3 L/min/m of applied flow, by Kernel estimation with a smoothing parameter of 0.1. (a) chisel plow plots, (b) moldboard plow plots, (c) conventional seedbed tillage plots, and (d) untilled stubble plots.

Table 5
Velocity distributions characteristics and rill cross sectional areas

Treatment	Flow applied (L/min/m)	Lower 50% of velocity range (m/s)	Higher 50% of velocity range (m/s)	Average final rill cross section (cm^2)
ChP	8.3	0.09–0.18	0.18–0.32	15.9
MP	8.3	0.16–0.23	0.23–0.29	50.1
CT	8.3	0.17–0.24	0.24–0.37	33.6
ST	8.3	0.08–0.12	0.12–0.19	0
ChP	12.4	0.09–0.17	0.17–0.27	16.4
MP	12.4	0.19–0.23	0.23–0.29	56.9
CT	12.4	0.17–0.23	0.23–0.33	26.2
ST	12.4	0.11–0.15	0.15–0.28	0
ChP	16.6	0.11–0.19	0.19–0.30	27.2
MP	16.6	0.20–0.26	0.26–0.38	103.8
CT	16.6	0.17–0.28	0.28–0.50	46.3
ST	16.6	0.10–0.16	0.16–0.30	16.6

MP: moldboard plow primary tillage; ChP: chisel plow primary tillage; ST: untilled stubble; CT: conventional seedbed tillage.

with the number of rills resulting from each tillage treatment with the flow application. For each treatment and flow applied, Table 5 indicates the ranges of flow velocity in both lower and higher 50% probability, and the average rill cross section measured at the end of the experiments.

In general, the velocities were less dispersed in the lower 50% of the cumulative probability and more dispersed in the upper 50% of probability. It is interesting to notice that the maximum velocities reached on the chisel plow plots at 8.3 and 12.4 L/min/m of flow rate were similar to those for the moldboard plots. Nevertheless, the flow velocity at 50% cumulative probability was lower in chisel plow and untilled stubble plots. In addition, there were fewer small-dimension rills, or no rills at all.

In conventional seedbed tillage, there was less oriented roughness resisting the water, and thus higher flow velocities resulted. It is important to mention the dynamics of rill formation in the conventional seedbed tillage treatment. At the beginning, rills were created at high flow velocities. Under that condition, rills could easily combine into fewer rills, but usually there was more than one rill per meter. In moldboard plow plots rill formation was slower. It took more time for water to pass from one furrow to the next. Once the water concentrated, the soil was easily eroded due to the low compaction of the soil surface under the moldboard plow, causing rills to gain more depth and width.

In the cases of untilled stubble and chisel plow, the residue reduced both the water velocity and concentration, thus impeding the movement of soil material. Therefore, the formation of rills was more difficult. Flow usually did not concentrate, but spread across in the plots. In this manner, the area covered by the flow was greater, flow depth was shallower, and flow velocity was reduced.

The above discussion shows that reducing flow velocity is necessary to avoid rill formation. The presence of residue covering at least 35% of the ground dramatically reduced the likelihood of rill formation. If rills were formed, residue reduced the capacity for transporting soil particles.

4. Conclusions

- The developed rill density model represents the factors that induce the generation of rills in the selected tillage treatments. In this research, flow applied, antecedent soil moisture content, and slope induced rill generation. Both the fraction of residue cover and the random roughness were inversely related to rill generation. The predictive model must be taken as a first approach. Further improvement may well be required.
- The assumption of considering one rill per meter was adequate in most cases. However, the formation of two rills every meter better represented the case

for the conventional seedbed tillage plots used in this study. It is necessary to point out the extreme conditions assumed for this research: application of clean water created a highly erosive condition on the soil. Also, the consideration of no infiltration is an assumption rarely found in the field.

- With the exception of the untilled stubble plots, flow application between 12.4 and 16.6 L/min/m generated a similar number of rills, although the cross-sectional area of the rills became larger as the flow applied increased from 12.4 to 16.6 L/min/m. This means that water preferred to erode the existing rill instead of creating more rills.
- In general, higher flow velocities implied the generation of more and larger rills, resulting in an increased capacity for transporting sediment.
- The high resistance to rill formation and erosion of the untilled stubble plots suggest this tillage system as the more adequate for agricultural areas traditionally vulnerable to soil erosion. In the same way, the tillage systems that do not maintain a residue cover on the ground must be avoided.

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